

Scuffing Behavior of 4140 Alloy Steel and Ductile Cast Iron

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ABSTRACT

Scuffing is a failure mechanism which can occur in various engineering components, such as engine cylinder kits, gears and cam/followers. In this research, the scuffing behavior of 4140 steel and ductile iron was investigated and compared through ball-on-disk scuffing tests. A step load of 22.2 N every two minutes was applied with a light mineral oil as lubricant to determine the scuffing load. Both materials were heat treated to various hardness and tests were conducted to compare the scuffing behavior of the materials when the tempered hardness of each material was the same. Ductile iron was found to have a consistently high scuffing resistance before tempering and at tempering temperatures lower than 427°C (HRC >45). Above 427°C the scuffing resistance decreases. 4140 Steel was found to have low scuffing resistance at low tempering temperatures, but as the tempering temperature increases, the scuffing resistance increased. Ductile iron and 4140 steel had the same scuffing resistance at a tempering temperature of about 538°C (ductile iron HRC 35-36; 4140 steel HRC 40). The scuffed specimens were studied using optical and scanning electron microscopy to determine the scuffing mechanisms and scuffing results were analyzed based on material microstructure and hardness.

CITATION: Mikecz, N., Kelley, N., Othman, E., Lumbreras, R. et al., "Scuffing Behavior of 4140 Alloy Steel and Ductile Cast Iron," *SAE Int. J. Mater. Manf.* 5(1):2012, doi:10.4271/2012-01-0189.

INTRODUCTION

The study of scuffing has been a subject of great interest in the automotive and industrial machine industry for many decades, yet definitions describing scuffing still vary. The *Fuels and Lubricants Handbook*, defines scuffing as "a form of wear occurring in inadequately lubricated tribosystems that is characterized by macroscopically-observable changes in surface texture [1]." Other definitions include descriptions of scuffing as visible surface scratches, polishing, plastic deformation, transferred material, increased wear rate, and, in severe cases, seizure of machined parts and solid-phase welding [1,2,3,4]. The definition for scuffing that will be used in this study is "a sudden catastrophic failure of

lubricated sliding surfaces characterized by a sudden rise in friction, contact temperature, vibration and noise, resulting in surface roughening through severe plastic flow and loss of surface integrity [5]."

Scuffing is a failure mechanism for various engineering components, such as engine cylinder kits, gears, crankshafts, and cam/followers [4]. Wear tests have been done on ductile iron and ferrous alloy steels, but the differences and comparison of scuffing resistance on martensitic ductile cast iron and martensitic 4140 alloy steel at different tempering temperatures have not been considered. 4140 alloy steel has been used in many industrial applications, but in recent years improvements have been made on mechanical properties of ductile iron so that they are similar to the mechanical

properties of many alloy steels [6]. 4140 steel and ductile iron can be quenched and tempered to obtain identical hardness values at similar tempering temperatures. Studying 4140 steel and ductile iron at the same hardness can show the effects of tempering and how martensitic ductile iron tribological properties compare to martensitic 4140 steel. Little testing has been done to compare the scuffing resistance of ductile iron to steels and if the scuffing resistance of the ductile iron is equal to or better than that of 4140 steel, perhaps it can replace the steel in some automotive applications.

Tribological studies of tempered ferrous steels and ductile irons have produced diverse results. Ambrosini et al. found that in sandblast tests with an increasing tempering temperature, 4140 steel erodes less. Although not directly comparable to scuffing, this research shows that tempering can have a positive effect on the wear resistance of 4140 steel [7]. Spheroidal graphite in martensitic ductile iron is thought to enhance plastic deformation and cracks on the surface during wear [6]. Other research has been done on comparing different types of cast irons, but very little studies have concentrated on comparing ductile irons and alloy steels [6, 8,9,10]. In studies of gray cast iron, it was found that in dry-sliding and low loading conditions a surface film on the surface was created by the graphite flakes, but later in the study it was found to cause debris in the wear track that ultimately led to severe wear [11].

The purpose of this study was to determine and compare the scuffing resistance of heat-treated martensitic ductile cast iron and 4140 alloy steel through ball-on-disk tests. After testing, the scuffing mechanisms were studied using optical microscopy and scanning electron microscopy.

EXPERIMENTS

TRIBOMETER

A ball-on-disk tribometer (BOD) was used to determine the scuffing resistance of the ductile iron and 4140 steel samples. The BOD consisted of a variable speed motor, rotating cup, ball, ball mount, belt drive, steel weights, and strain indicator, as shown in Figure 1. An optical tachometer was used to determine the speed of sample rotation. The ball was a 7.9375 mm diameter E52100 alloy steel ball (60 to 67 HRC). The coefficient of friction between the ball and disk was determined using the normal load and the frictional force, which is measured using the strain indicator attached to the mount.

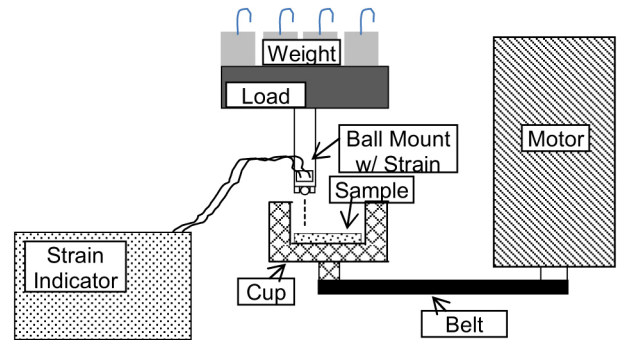


Figure 1. Schematic of ball-on-disk (BOD) tribometer

TEST PROCEDURE

For the scuffing resistance tests, the sample was mounted into the cup and the steel ball was secured in the ball mount. The rotating speed was set to 73.3 rad/s and the radius was adjusted to 20mm which resulted in a sliding velocity of 1.47 m/s. Initially, three mL of light mineral oil at a viscosity of 33.5 cst at 40°C were added to the sample. A 22.2 newton load was added every two minutes, with a re-lubrication of six drops (approximately 0.1 mL) immediately after each load. The test was stopped after a sharp increase in frictional force that continued to rise (as shown on the strain indicator), along with a loud grinding noise and vibrations. The load at this moment is referred to as the scuffing load.

The wear track on each sample was then studied under the optical microscope to study the size and condition of the track, defects, or points of interest found, including material transfer, cracking, and deformation. A selection of samples were chosen and cut to be mounted and polished for an examination of the microstructure of the material under the wear track; other samples were chosen to be viewed under the Scanning Electron Microscope (SEM) for a high resolution image of the materials' surface and an X-Ray Photoelectron Spectrometer (XPS) was used to determine if films had formed during the scuffing test.

TEST SAMPLES

Samples consisted of 4140 alloy steel and ductile cast iron (DI). Both materials had a martensitic matrix. In addition, the ductile iron had large graphite nodules in the martensitic matrix. The samples were quenched and then tempered at 149°C, 204°C, 316°C, 427°C, 538°C, 566°C (DI only), 593°C, and 649°C (4140 only); the DI also had a quenched only group of samples as shown in Table 1.

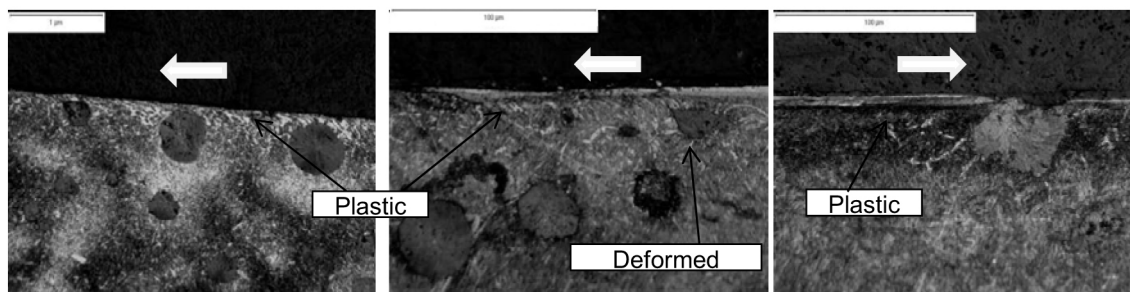


Figure 2. Cross section of scuffed ductile iron from samples 60 HRC (left), 46 HRC (middle), 25 HRC (right)

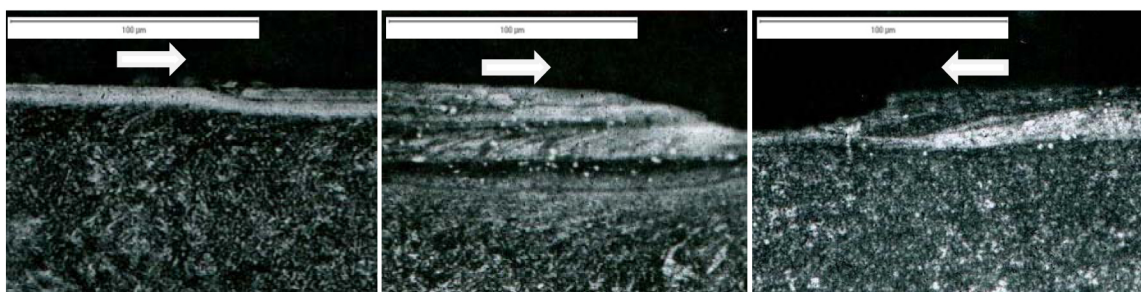


Figure 3. Cross section of scuffed 4140 steel samples 51 HRC (left), 40 HRC (middle), 30 HRC (right)

Table 1. Table of specimen tempering temperature/hardness

Ductile Iron			4140 Steel		
Before Temper	After Temper		Before Temper	After Temper	
HRC	HRC	Temper (°C)	HRC	HRC	Temper (°C)
58-60	58-60	Quenched Only	57-60	55-59	149
	56-57	149		55	204
	54-55	204		51	316
	52-53	316		46	427
	45-46	427		40	538
	35-36	538		36-37	593
	31-32	566		29-30	649
	25	593			

The samples were quenched to a HRC value of about 60, and became softer with an increasing tempering temperature. Six samples from each group were tested (except for the softest 4140 group which only had four samples tested). The arithmetic average surface roughness, R_a , of each sample was approximately the same, in a range of 0.4 to 0.7 micrometers.

RESULTS AND DISCUSSION

MICROSTRUCTURE

Since both materials have a martensitic matrix, the biggest difference between them is the graphite nodules present in the ductile iron. These nodules are visible in the far left and middle photographs in Figure 2.

From observation of the subsurface under the optical microscope, it's apparent that martensitic ductile iron failed by plastic deformation as shown by the plastic flow and deformed graphite in Figure 2. It can also be seen in the black band in the rightmost image that there was enough heat generated in the scuffing test to further temper the martensite matrix. Although there is some visible plastic deformation in the 4140 steel samples, shown in Figure 3, there is more evidence of cracking in those samples when viewed with the SEM (discussed later).

SCUFFING RESULTS

Figure 4 shows the scuffing load versus tempering temperature for the ductile iron and 4140 steel specimens. At higher tempering temperatures, the scuff resistance of ductile iron decreases whereas 4140 steel has a higher scuff resistance at higher tempering temperatures.